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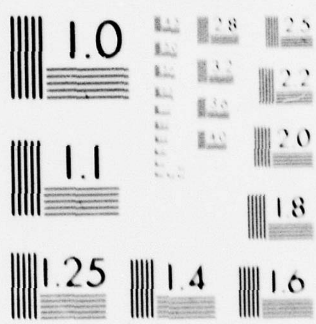
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Research and Development Technical Report

ECOM-77-2713-1

LINEAR 1 kW MULTITONE TROPOSCATTER TWT

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Electron Dynamics Division
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MAY 1978

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This report covers the first triannual effort of a Research and Development program to design, construct, and test an advanced high efficiency traveling-wave tube designed to amplify multiple signals while minimizing and mixing products which result from non-linear operation. The tube will be operated in the linear region below saturation; tube efficiency will be enhanced by means of a four-stage depressed collector.

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20. The electron gun was scaled to the proper perveance and area convergence. Parts were ordered to check the scaled gun in the demountable beam analyzer.

Preliminary thermal calculations have indicated that the tube can be air-cooled. The iron cavity walls, used in periodic permanent magnet focusing of the coupled cavity caircuit, will be laminated with copper. A beam scraper section will also be incorporated for improved thermal dissipation.

Parts and fixtures have been ordered to do the impedance matching of the RF interaction circuit.

The mechanical design of the four-stage depressed collector has been started.

PURPOSE

The purpose of this program is to design, construct, and test an advanced high efficiency traveling-wave tube in accordance with U.S. Army Electronics Command, Beam, Plasma and Display Technical Area Guidelines "MW-114 for the Linear 1 kw Multitone Troposcatter Traveling Wave Tube," dated 20 October 1976. This tube will be designed to amplify multiple signals while minimizing any mixing products which result from non-linear operation. It will operate at a power output of 1.0 kW CW with a gain of 40 dB over the 4.4 to 5.0 GHz frequency band. It will be operated in the linear region below saturation. Overall tube efficiency will be enhanced by means of a multiple stage depressed collector. The tube will use a coupled-cavity interaction circuit with integral permanent magnet beam focusing. Air cooling is an objective.

The program calls for the delivery of one exploratory developmental model representative of the work accomplished under the development effort. The length of the program is twelve months.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The basic objective of the present program is to demonstrate an optimum traveling-wave tube (TWT) design for applications in tactiical troposcatter communications systems. The design of this tube will be based on the data presented in the Research and Development Technical Report ECOM-75-1283-F. The primary design concept is to operate the tube below saturation in order to achieve the low intermodulation (IM) requirements. To achieve the required performance characteristics the tube will be operated approximately 6 to 7 dB below saturation. At the rated power of 1.0 kW minimum, the basic efficiency of the tube will be approximately 4 percent. To improve the overall efficiency of the tube, a four-stage depressed collector will be used to recover most of the kinetic energy in the spent beam. The original design study indicated that the overall efficiency can be increased to a minimum of 25 percent by using this technique.

The specification for the multitone troposcatter TWT is presented in Table I.

Periodic permanent magnet (PPM) focusing of the electron beam and air cooling are objectives of the tube design because the overall efficiency will be greater if PPM focusing is used in place of conventional solenoid focusing with the attendant solenoid power supply and air cooling will make the tube more compatible with existing troposcatter transmitters. However, the use of air cooling does place stringent requirements on the thermal design. Initial calculations were made which indicated that it is possible to cool a PPM focused, coupled-cavity tube of this power level with forced air. Therefore, that is the approach being used for the multitone tube.

TABLE 1

SPECIFICATION FOR MULTITONE TROPOSCATTER TWT 673H

Electrical Requirements:	
Frequency Range	4.4 - 5.0 GHz (Min)
Power Output CW	1 kW (Min)
Gain	40 dB (Min)
Instantaneous Bandwidth (-1 dB)	15 MHz (Min)
Beam Voltage	-26 kV (Max)
Beam Current	1.5 A (Max)
Efficiency (Note 1)	25% (Min)
Intermodulation (Note 2)	-20 dBC
Output Load VSWR	1.5:1 Max
Focusing	PPM (Objective)
Life	10,000 Hrs. (Objective)
Mechanical/Environmental:	
Size	To Be Determined (TBD)
Weight	To Be Determined (TBD)
Cooling	Air (Objective)
RF Input Connector	Type N Coax
RF Output Connector	WR-187 Waveguide/UG-149/Flange
Altitude (Operating)	3,100 Meters
Ambient Temperature (Operating)	$-50^{o}C$ to $55^{o}C$
Mounting (Operating)	0 to 15^{o} from Vertical
Shock (Non-operating)	50 G, 1 msec
Vibration (Non-operating)	5 to 55 Hz 1.02 cm Amplitude 5 ± 0.5 Minutes

Note:

1. The overall TWT efficiency is defined as: RF output power divided by the sum of beam input power, cooling power, focusing power, and heater power. The tube shall be capable of meeting the efficiency specified under conditions where the IM products are within the specified limits with 4 to 16 signals applied to the input.

2. The intermodulation products requirement will be met over any 15 MHz band in the 4.4 GHz to 5 GHz frequency range. The 15 MHz band will be divided into sixteen adjacent equal bandwidth channels. Anywhere from 4 to 16 of the channels will be occupied by carriers. The total intermodulation power in any occupied channel shall be 20 dB below the carrier in that channel. The carrier output power of all the occupied channels shall total 1 kW.

The theoretical electrical characteristics of the tube were described in detail in the earlier report, ECOM-75-1283-F. The purpose of the present program is to construct a tube having the previously determined design parameters and measure its operating performance. This effort consists chiefly of the following areas:

1. An electron gun will be scaled to the required beam size, area convergence, and perveance and mounted in an existing isolated anode support structure.

2. The RF interaction circuit and integral PPM focusing structure will be designed. This includes determining the final circuit dimensions to give the required phase shift characteristics, providing adequate circuit loss for stability, and matching the circuit to internal sever terminations, an input coaxial coupler, and an output waveguide step transformer and window.

3. The mechanical design of the four-stage depressed collector will be accomplished, taking into account the voltage standoff and thermal dissipation requirements, using the electrode configuration that had been determined previously.

4. The overall packaging and cooling structure of the tube will be designed.

5. The experimental tube will be fabricated and tested.

During the first triannual period of the program the electrical design of the electron gun was accomplished, circuit parts and test fixtures were ordered for designing the interaction structure, and the mechanical design of the collector and packaging were started. The tube has been given the Hughes designation 673H.

2.0 ELECTRON GUN

In determining the design for the multitone tube, parameters were chosen to achieve the highest overall efficiency within the distortion specification of 20 dB carrier-to-IM (C/IM) power ratio. This requires operating the tube 6 to 7 dB below saturation to meet the C/IM requirement and using a four-stage depressed collector to increase the overall efficiency. For high overall efficiency it is necessary to have a high basic tube efficiency at the backed-off condition, good beam transmission to the collector, and effective collector performance.

To ensure good beam transmission in a PPM focused device, the focusing quality parameter λ_p/L (plasma wavelength divided by the magnetic period) is made 3.5 or larger. With a given operating voltage and current, the interaction strength is then maximized by choosing the beam hole as small as possible consistent with the λ_p/L constraint, assuming a beam radius to drift tube hole radius (b/a) of 0.6.

A calculation of Pierce's gain parameter C was performed as a function of the beam voltage, assuming a constant beam power of 20 kW and using a minimum beam hole size consistent with $\lambda_p/L = 3.8$. Under these conditions the C parameter was nearly independent of voltage. The choice of operating voltage was, therefore, made with good collector performance in mind. A high-voltage, low-perveance design has smaller space charge density in the beam, which tends to make it easier to sort the electrons in the collector according to their energy. Furthermore, a high voltage permits a small beam hole with a low radial propagation parameter γa. This helps to reduce the RF defocusing in the beam, resulting in improved beam transmission and decreased spread in electron trajectory angles. Both of these conditions are desireable for high efficiency enhancement with the multi-stage collector. A high voltage

also increases the axial dimensions of the interaction circuit which improves its thermal dissipation capability.

The final operating parameters chosen for the 673H are a beam voltage of 25 kV and a current of 1.3 A. The electron gun will be a Pierce type convergent flow gun with an area compression of 16:1 to assure low cathode emission current density and long life. The required characteristics of the gun, designated the Hughes 238B, are summarized in Table II.

The scaling of the 238B gun has been completed, subject to verification of the gun performance in the demountable beam analyzer.

For the gun design, use was made of empirical design curves depicting the relationships between perveance, cathode half-angle, and beam size for the desired cathode diameter. The electrolytic tank, shown in Figure 1, was then used to establish the electrode configuration and relative spacings. These determinations are made by first computing what the theoretical beam edge potential distribution should be, given the gun perveance, cathode radius, and $\overline{r}_c/\overline{r}_a$ (the ratio of the sperical cathode radius to the effective spherical anode radius). Then models of the focus electrode and anode are adjusted until the best possible match to the theoretical beam edge distribution is achieved. The result of this procedure is shown in Figure 2.

Next, the Hermansfeldt computer program, which solves Poisson's Equation for a cylindrical boundary problem, was used to predict the axial potentials, perveance, and non-thermal electron trajectories. A computer generated description of the 238B gun is shown in Figure 3.

TABLE II

238B ELECTRON GUN DESIGN PARAMETERS

Cathode Voltage	-25 kV
Cathode Current	1.3 A
Perveance	0.33×10^{-6}
Cathode Loading	1.1 A/cm^2
Nominal Beam Diameter	0.121 inch
Area Compression	16:1
Cathode Material	Impregnated tungsten
Magnetic Field	PPM
Magnetic Period	1.036 inch

When the perveance parameter and computer perveance agreed, another computer program, which takes into account thermal electron velocity effects, used the axial potentials, the relevant gun parameters, and an assumed magnetic field distribution to compute the focused electron beam shape. The electrostatic beam envelopes was also predicted for a thermal beam using this program. Figure 4 shows the computer generated plots for the electrostatic beam of the 238B electron gun. Five beam envelopes are shown. The envelopes containing 99.5 percent and 95 percent of the beam current are labeled $r_{99.5}$ and r_{95} respectively. The beam radii where the current density is 1/10 and 1/20 the peak current density are indicated by $r_{1/10}$ and $r_{1/20}$ respectively. The fifth radius, r_o, is the statistically averaged beam radius. Typically, the program computes the minimum beam position about 10 percent less than is

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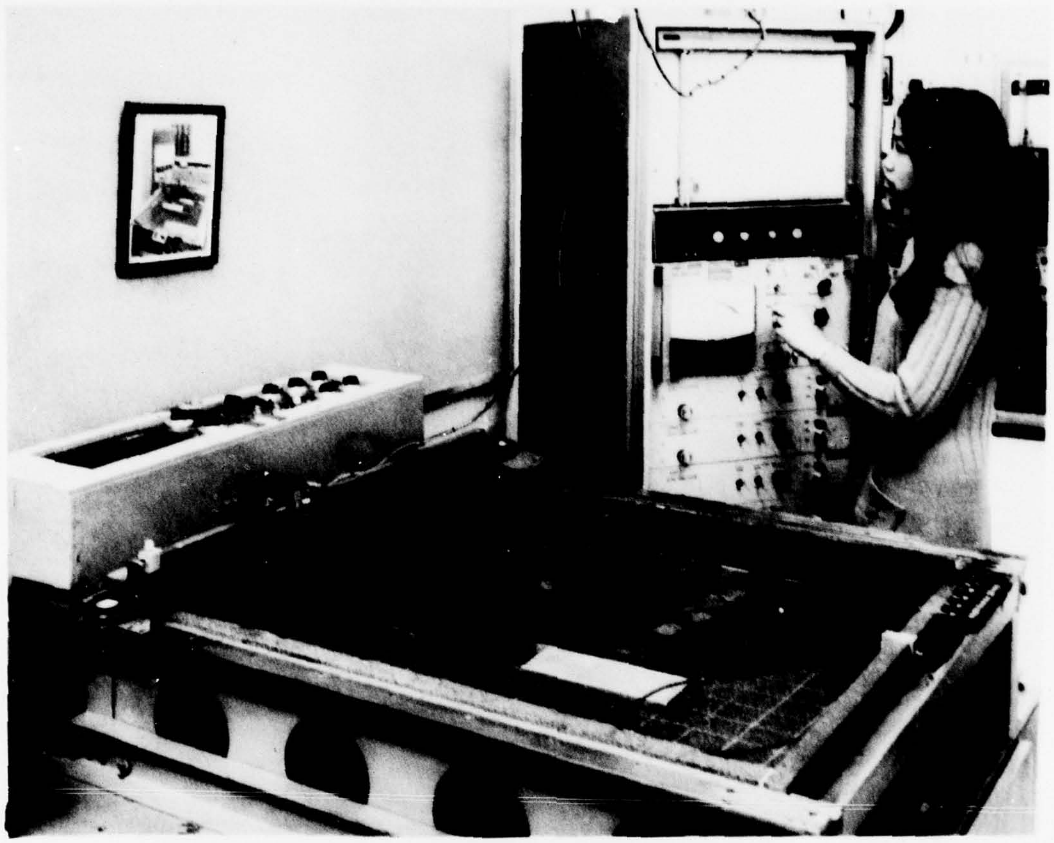

Figure 1 Electrolytic tank.

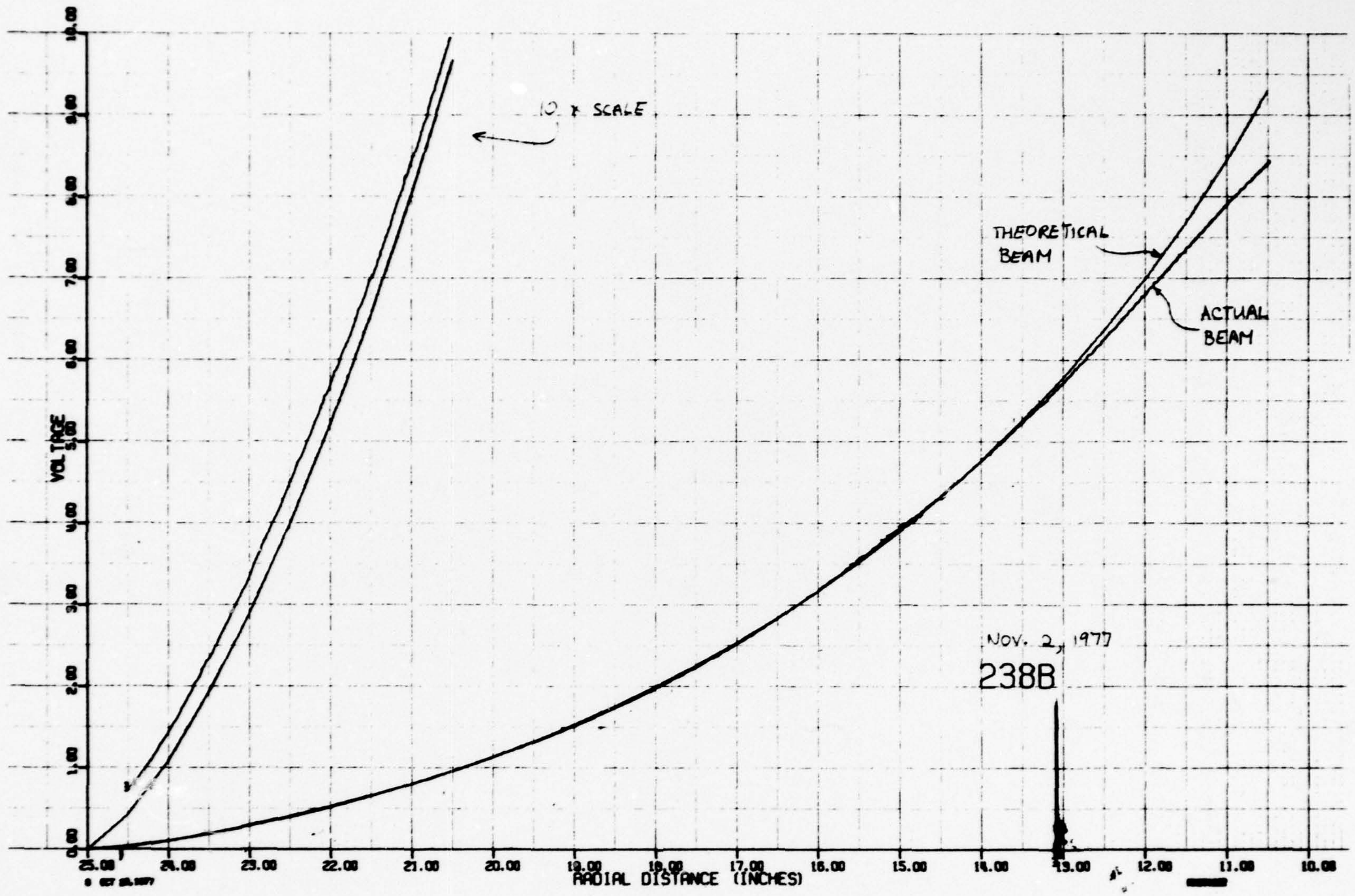

Figure 2 Theoretical and electrolytic tank measurements of beam edge potential for 238B electron gun.

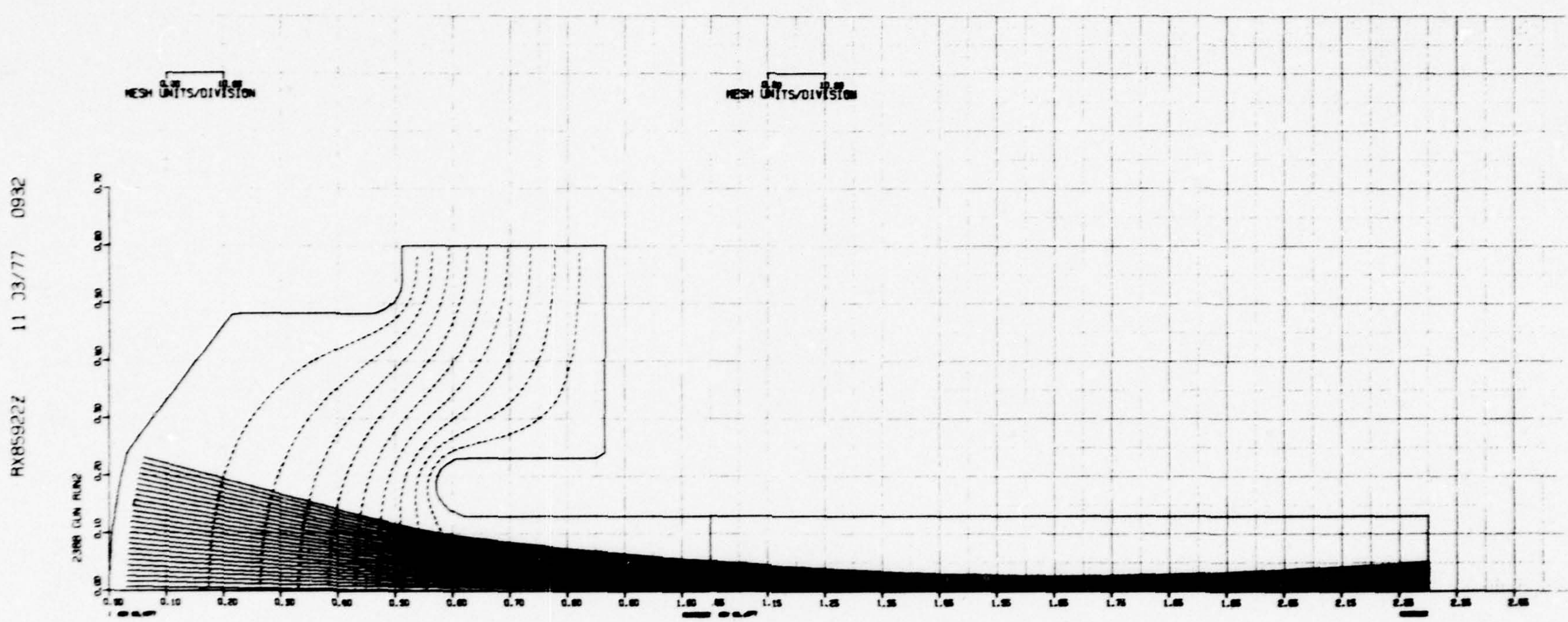

Figure 3 Computer generated electron trajectories and potential distribution of 238B electron gun.

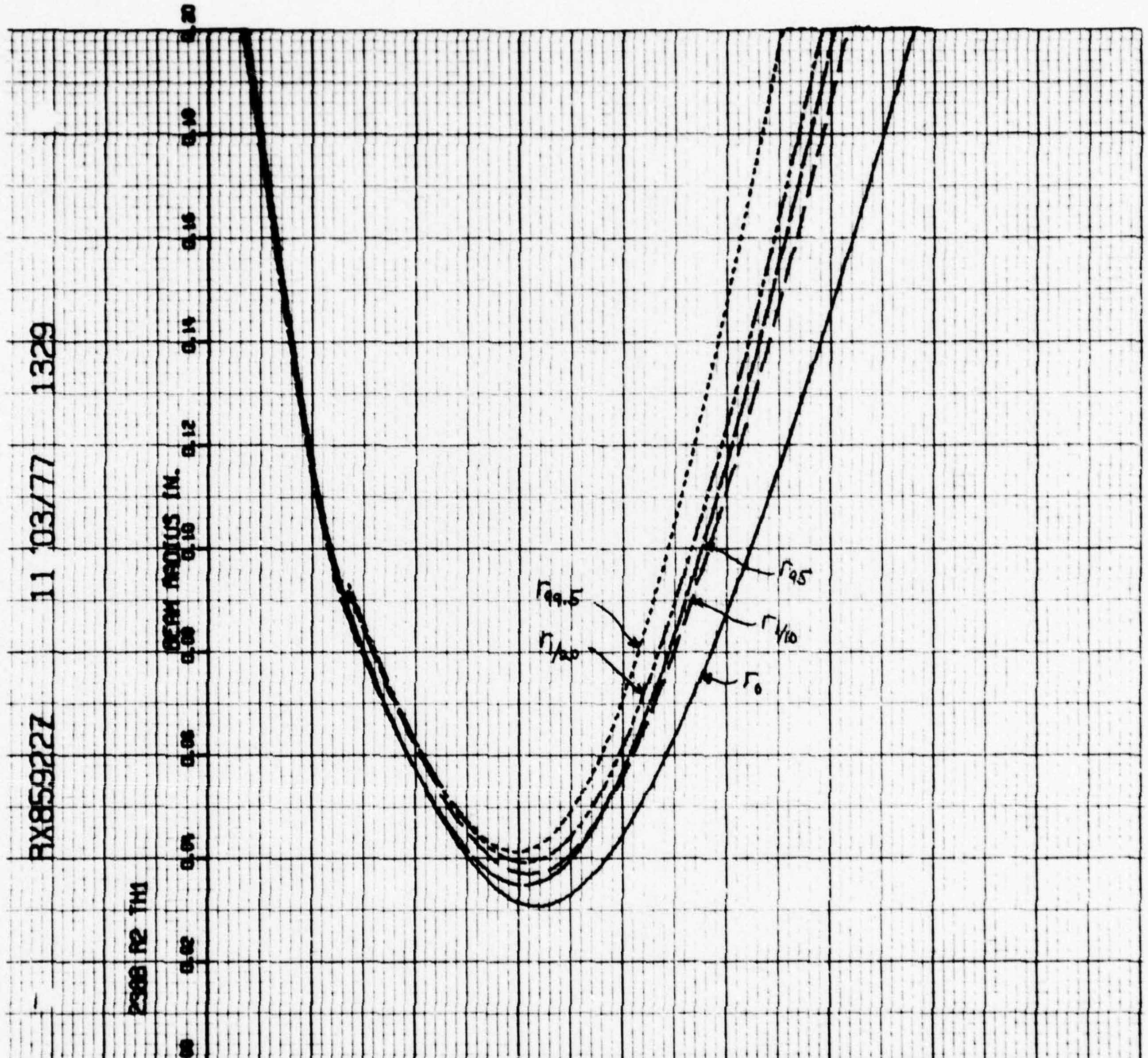

Figure 4 Computed electrostatic beam envelopes of 238B gun.

measured; so the cathode valley to the beam minimum position is predicted to be 1.59 inches. This will be verified later by measurements in the demountable beam analyzer.

An optimized computer run for the focused beam is shown in Figure 5. The focusing field for this case has a peak amplitude of 1350 gauss. This optimum focusing occurs when the first magnetic field is 0.240 inch downstream from the electrostatic beam minimum position.

Parts have been ordered to build an "A" scale gun for checking in the beam analyzer. For the 238A gun, the 238B gun just discussed was scaled by a factor of 0.911 in order to achieve a scaled cathode diameter of 0.440 inch, which is compatible with the analyzer test fixtures.

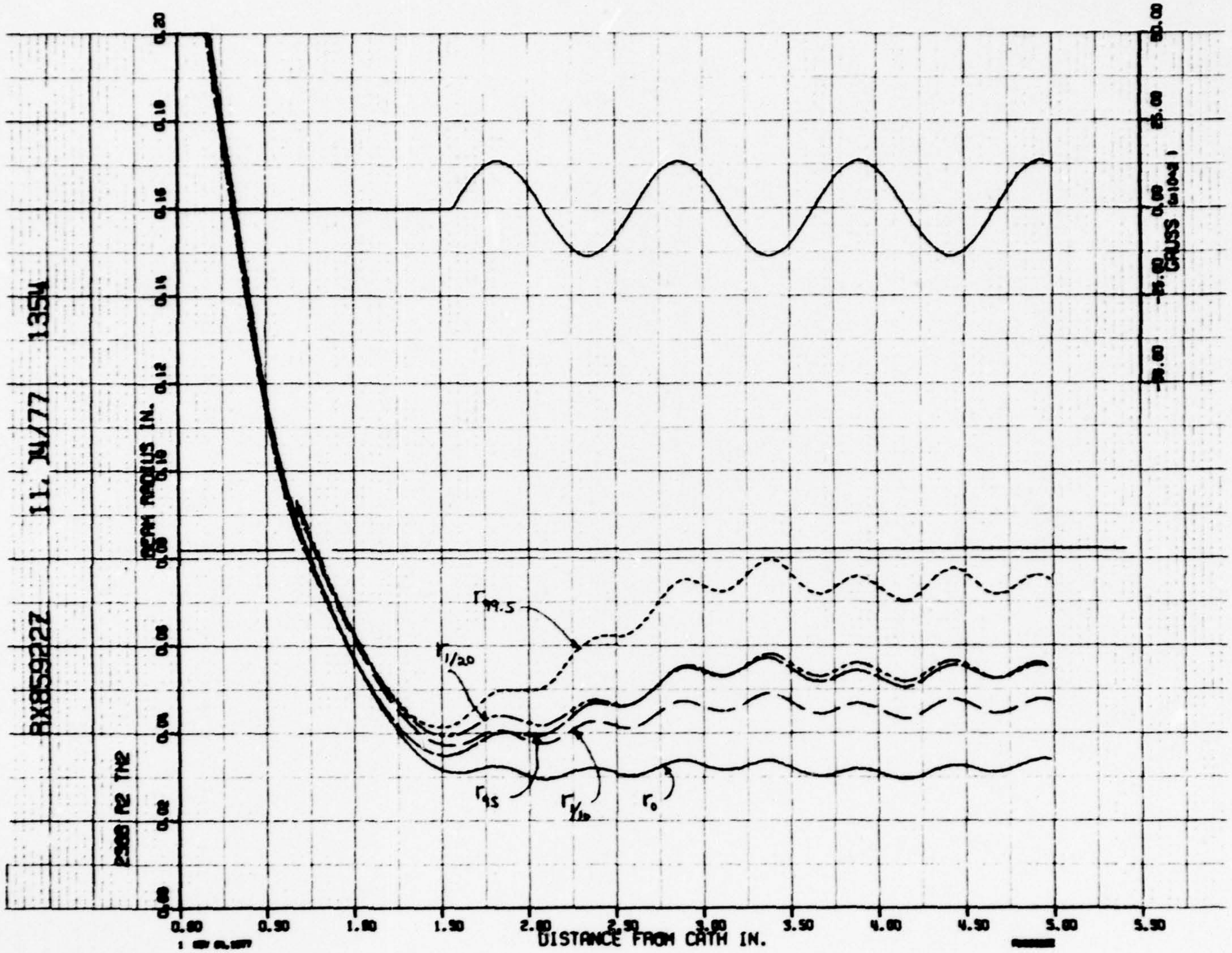

Figure 5 Focused beam characteristics for 238B electron gun.

3.0 INTERACTION CIRCUIT

The general circuit parameters for the multitone tube were determined in the previous study program. The theoretical phase-vs-frequency (ω-β) characteristic used in the study is shown in Figure 6. The basic cavity configuration is presented in Figure 7. Values of the outer diameter, coupling hole angle, and cavity gap are approximate; these dimensions will be adjusted during cold testing to give the desired ω-β response.

In a PPM focused coupled-cavity TWT, the cavity walls are made of iron. They serve as pole pieces for concentrating the magnetic field in the proximity of the electron beam. The focusing magnets are situated between adjacent pole pieces and just outside the copper spacers, which form the cavity outer diameter. Cooling of the pole pieces is critical because runaway conditions can be encountered if the temperature of the pole piece is allowed to approach the Curie temperature of the iron. The beam and circuit parameters were chosen with the aim of providing excellent beam transmission. Nevertheless, it must be assumed that some beam power will be intercepted on the interaction circuit.

Calculations were made of the temperature rise from the outer cavity diameter to the tip of the drift tube ferrule, where the beam is intercepted. This temperature rise will depend upon the amount of the intercepted beam power. For the calculation a worse case transmission of 98 percent was assumed with a total beam power of 32.5 kW. This interception will be spread along the circuit. It was also assumed that, at most, one-tenth of the total intercepted power or 65 watts hits any one ferrule. (A beam scraper section is planned at the input of the circuit near the gun end, so possible higher interception in that region is not considered here.) For iron cavity walls the temperature

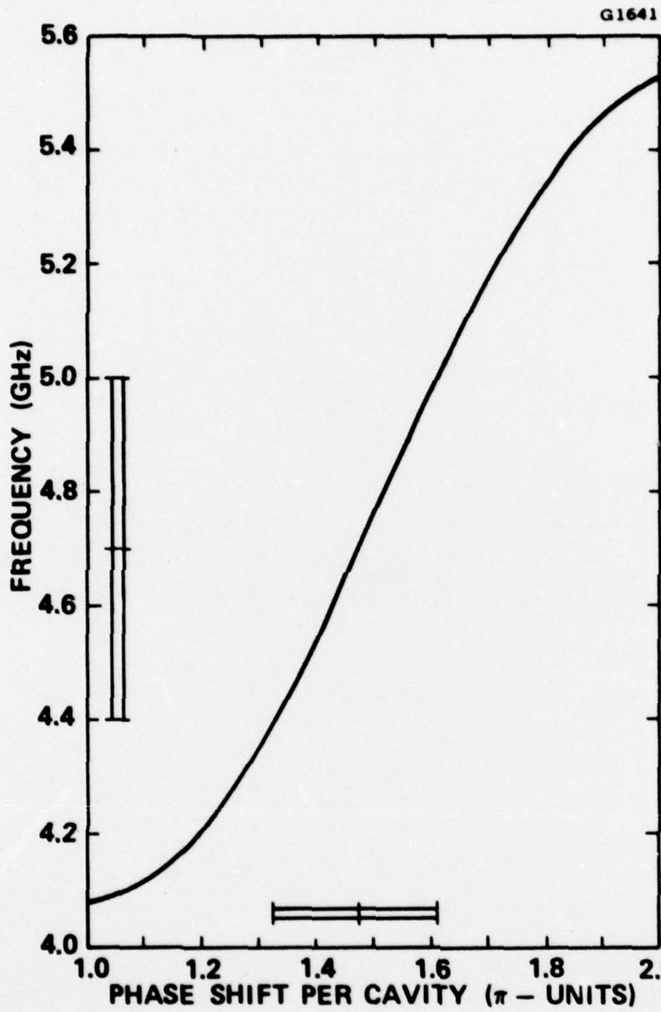

Figure 6 Theoretical frequency-vs-phase (ωβ) characteristic of interaction circuit.

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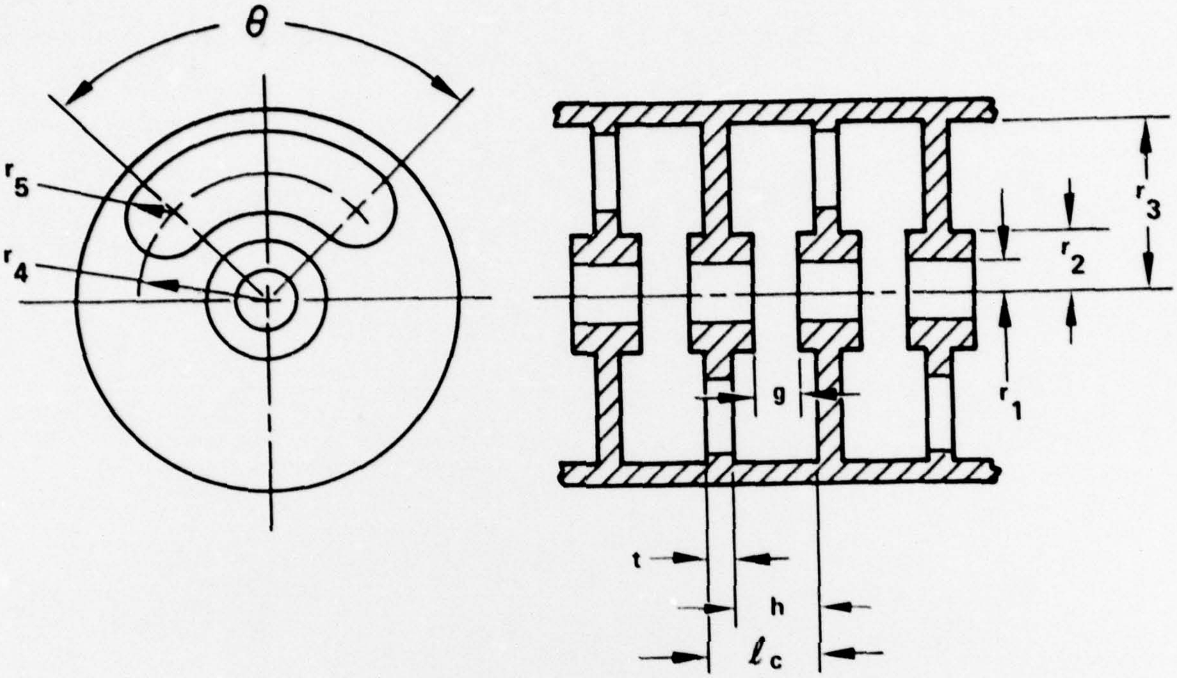

$2r_1$ = .202 in	ℓ_c = .518 in.
$2r_2$ = .282 in.	t = .080 in.
$2r_3$ = 1.182 in.	g = .135 in.
$2r_4$ = .790 in.	$\theta = 100^o$
$2r_5$ = .390 in.	

Figure 7 Preliminary cavity dimensions.

rise was calculated to be 600 degrees C. The actual ferrule tip temperature has to be increased by the ΔT from the cavity OD to the coolant. This value of temperature rise would be completely unsatisfactory, even if liquid cooling were substituted for the air.

To improve the thermal capability of the circuit, the following changes were made:

1. The cavity walls were increased in thickness from 0.080 to 0.118 inch. The thicker cavity wall results in a slightly reduced circuit impedance, which lowers the calculated tube efficiency by about 0.4 percentage points.

2. The ferrule radial thickness was not increased because that would have reduced the impedance and efficiency more drastically. However, the ferrule outer diameter will be tapered to a larger diameter at the base of the ferrule, where it joins the cavity wall. This will improve the thermal conduction without appreciably affecting the interaction impedance.

3. Copper laminations will be introduced on the iron pole pieces. This technique is effective because copper has a thermal conductivity approximately seven times as high as iron.

The incorporation of these modifications in the circuit structure has reduced the calculated temperature rise from the cavity OD to the ferrule tip to 66 degrees C. This is a reasonable value for an air cooled tube.

Cold test parts have been ordered to determine the final circuit dimensions for the desired ω-β characteristic. Pole piece blanks, from which

the laminated cavity walls will be fabricated, have also been ordered, as have the other circuit parts and matching fixtures for use when the final circuit dimensions have been determined.

Alnico 8 magnets will be used to focus the beam. The calculated peak axial field, neglecting fringing effects, is 2900 gauss. The magnets will be shunted to provide the optimum focusing field in the tube. They have been ordered.

The coaxial input window and coupler and the poker chip waveguide output window are being used directly from other existing tubes. The waveguide step transformer for matching the tube circuit to full height waveguide has been designed and ordered.

4.0 COLLECTOR AND PACKAGE

The multi-stage depressed collector is the key element in achieving high overall efficiency on the 673H. The basic efficiency of the tube has been theoretically predicted to be a minimum of 4 percent across the frequency range of 4.4 to 5.0 GHz. To increase the overall efficiency of the tube to 25 percent will require that the spent beam be collected in a manner which will recover most of its kinetic energy.

The multi-stage collector has three electrical functions:

1. To sort the electrons in the spent beam according to their energies

2. To slow the electrons that they may be collected with their lowest possible kinetic energy, thereby minimizing collector dissipation and maximizing overall efficiency

3. To prevent backstreaming of both reflected primary electrons and secondary electrons.

The design of the collector required optimization of the shape, position, and depression potential of each electrode. This optimization was performed during the previous study program. Figure 8 is a reproduction of a computer-generated plot of the collector design for the 673H. The solid lines are trajectories and the dashed lines are equipotentials. The spent beam, which enters from the left, is made up of six energy groups with four rays each. The depression increases with distance into the collector. The depression voltages were chosen to be 50, 81, 88 and 97 percent of the cathode voltage from the energy distribution calculations of the spent beam.

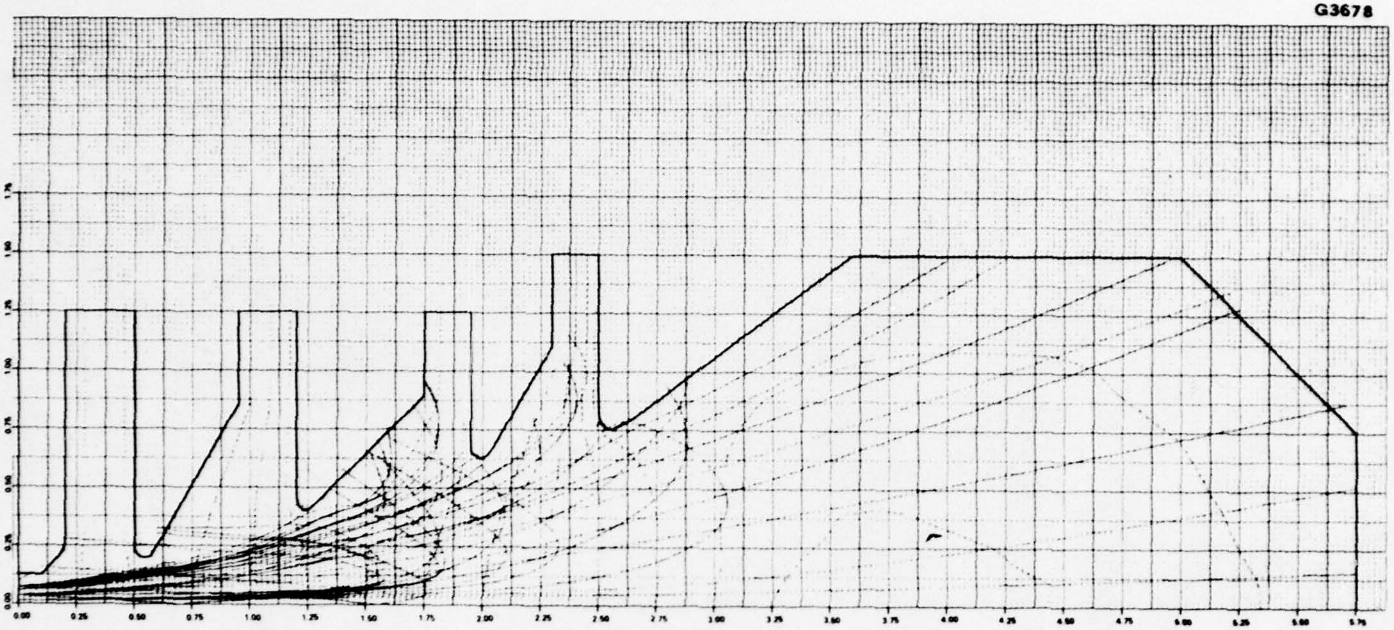

Figure 8   Four-stage depressed collector for the multitone tube (scale in inches).

The thermal and mechanical design of the four-stage depressed collector is very complex and critical. The primary design criteria for this collector is to provide the relatively high electrode standoffs for the four electrodes as previously determined and at the same time provide a good thermal path out to the air-cooled fins.

The planned technique for achieving these requirements is to completely enclose the four electrodes within a ceramic cylinder. This ceramic will provide both electrical isolation and good thermal conduction for the collector elements. Using this technique, the electrical standoff for the collector is located within the vacuum envelope, eliminating the possibility of externally contaminating the insulator surface, which would eventually result in arcing. The electrical connections are made through conventional, high voltage feed throughs. This design is based on an existing four stage collector previously developed at Hughes.

The mechanical assembly of the collector will be achieved by brazing the four electrodes to the inner diameter of the metallized ceramic cylinder. The electrodes will be stress relieved to prevent fracturing the ceramic during temperature cycling.

Attachment of the feedthroughs and final assembly of the collector to the tube body will be accomplished by heliarc welds.

The most critical area of assembly will be the attachment of the cooling fins. At the present time the detail mechanical design and thermal calculations are in progress. The cooling fins can be brazed directly to the outer wall of the metallized ceramic, which will provide excellent thermal contact. However, there is danger of fracturing the ceramic due to the differential thermal expansions of the materials involved.

If the fins are clamped to the ceramic, the assembly will be simpler, but the thermal interface will not be as good. Both approaches are being investigated. The final choice will depend upon the results of the thermal calculations and experimental assembly fabrication.

The large alumina insulator ceramic, which is a long lead item, and the feedthroughs have been ordered.

The design of the package has been started, however, the final details will not be completed until the thermal design of the collector has been finalized. The package will provide both structural rigidity to the tube and a means of air cooling the body and collector. To cool the RF circuit a cooling fin will be mechanically attached to the outer diameter of the pole pieces using an interface of quilted copper and heat paste. The package will consist basically of a carriage into which the tube is mounted. It will provide the required ducting to route the cooling air across the circuit fins and then the collector fins. Mounting feet will be included on the base of the package.

5.0 PLANS FOR NEXT PERIOD

1. The scaled 238B electron gun will be checked in the demountable beam analyzer. The final scaling factors will be determined. The mechanical design will be completed, parts will be procured, and the gun for the tube will be fabricated.

2. Phase shift measurements of the RF interaction circuit will be completed. Circuit parts for the tube will be procured. Matching of the circuit and fabrication of subassemblies will be started.

3. The mechanical and thermal designs of the collector will be completed. Parts will be ordered. Fabrication of subassemblies will be started.

4. The external package design will be completed.

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